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Preliminary Experimental Measurement of Isoplanatic Angle

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Lincoln Laboratory
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LEXINGTON, MASSACHUSETTS

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This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

Hugh L. Southall

Hugh L. Southall, Lt. Col., USAF
Chief, ESD Lincoln Laboratory Project Office

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

PRELIMINARY EXPERIMENTAL MEASUREMENT OF ISOPLANATIC ANGLE

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Group 67

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ABSTRACT

Group 67 has designed and built an isoplanometer, an instrument which remotely senses the isoplanatic angle associated with short-term atmospheric conditions. Verification of the instrument required nighttime testing using stellar sources to measure current atmospheric conditions. Preliminary results from a verification experiment and a brief description of the instrument are presented. Full instrument verification requires locating the instrument at a better astronomical site; therefore, our data should not be considered a valid characterization of the atmospheric conditions in Lexington, Massachusetts.

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PRELIMINARY EXPERIMENTAL MEASUREMENT OF ISOPLANATIC ANGLE

I. INTRODUCTION

Group 67 has designed and built an isoplanometer, an instrument which remotely measures the isoplanatic angle associated with atmospheric turbulence conditions. The isoplanatic angle is loosely defined as the angular field over which the spatial transfer function of the atmosphere can be assumed to be invariant. The theory and design of the isoplanometer are detailed in a separate document.[1] Here, a brief review of the theory and a description of the instrument constructed are given. Isoplanatic angle data are presented for a single measurement session, taken from the A-building roof of Lincoln Laboratory on 25 July 1988. Measurement procedures and instrument verification tests also are discussed. This report documents the operation of the instrument (which was designed to operate only under "good" atmospheric seeing conditions), but does not document atmospheric conditions in Lexington, Massachusetts. These preliminary measurements should not be used as verified data.

II. THEORY

For completeness, we review the theory used for these measurements. The basis of the theory is the relationship (first suggested by Loos and Hogge[2]) between the observed intensity fluctuations of starlight and the isoplanatic angle. The resulting measurement technique is indirect,[3] a crucial point since a direct measurement would require a large amount of airborne equipment at considerably greater complication and expense.

Consider a telescope whose aperture has been apodized by a circularly symmetric, spatially varying intensity mask. Let the intensity transmittance of this mask be defined by $P(\rho)$, where $0 \le P(\rho) \le 1$, and ρ is the radial distance to the center of the mask. The optical power collected from a star viewed through this apodized telescope is denoted as S. Atmospheric turbulence causes starlight intensity to vary (twinkle); therefore, S is time variant. It can be shown that the normalized variance of the received intensity fluctuations of a star observed through the apodized telescope aperture is given by[1]

$$\sigma_\zeta^2(\phi_z, \lambda) = 4(2\pi)^4 0.033 \sec^{8/3}(\phi_z) k^2 A^{-2} \int_0^\infty C_n^2(z)\, W(z)\, dz \qquad (1)$$

where

$A = 2\pi \int \rho\, P(\rho)\, d\rho$

$k = 2\pi/\lambda$ (λ = viewing wavelength)

ϕ_z = viewed zenith angle of the star

z = slant range distance to the star

$C_n^2(z)$ = refractive structure parameter of the atmosphere measured along the slant range path to the star

$$W(z) = \int_0^\infty \left| \int d\rho\, \rho J_0(L\rho)\, P(L\rho) \right|^2 L^{-8/3} \sin^2\left[\frac{L^2 z}{2k}\right] dL$$

Equation (1) explicitly indicates that the normalized variance is a function of both zenith viewing angle ϕ_z and viewing wavelength λ ($k = 2\pi/\lambda$). The wavelength dependence, however, is a small second-order effect,[3] and thus the wavelength dependence of $\sigma_s^2(\phi_z)$ will be dropped.

Equation (1) was derived under the assumption of weak scattering, but the result is known to remain valid even outside this regime.[3-6] There is some σ_s^2 value, however, beyond which Equation (1) is no longer correct. This maximum value is a function of the mask $P(\rho)$, and its determination is an area of active research. When σ_s^2 is less than the allowed maximum, the normalized variance is said to be unsaturated, and the results of the isoplanatic angle approximation presented below are considered valid.

The isoplanatic angle θ_0 measured along the slant path z is given by[7-8]

$$\theta_0(\phi_z,\lambda) = 0.527\, k^{-6/5}\left[\int_0^\infty C_n^2(z)\, z^{5/3}\, dz\right]^{-3/5} \text{radians} \tag{2}$$

The zenith-angle dependence is inherent in the slant path z. If an apodizing mask $P(\rho)$ can be chosen such that $W(z) \cong cz^{5/3}$, then it follows from Equations (1) and (2) that the observed starlight intensity fluctuations can be related to the isoplanatic angle by

$$\theta_0(\phi_z,\lambda) = 12.9 \sec^{-8/5}(\phi_z)\, A^{-6/5} c^{3/5}\left[\sigma_s^2(0)\right]^{-3/5} \tag{3}$$

which is the desired result.

A mask satisfying $W(z) \cong cz^{5/3}$ at a wavelength of λ = 5000 Å was found by an exhaustive search algorithm. The search was restricted to binary masks [i.e., $P(\rho) = 0$ or 1], since they are easier to fabricate. The masks examined were required to fit on an 8-in-diam. Celestron Schmidt-Cassegrain telescope to be used in the experiment. The telescope has a 2.8-in-diam. secondary mirror obscuration; therefore, $P(\rho) = 0$ for $\rho < 1.4$ in. Figure 1 shows the mask solution obtained by exhaustive search. The black areas of the mask are totally obscuring; the white areas are assumed to be 100-percent transmissive. The radii of the optimum mask are as follows:

Central obscuration	1.4-in radius
Telescope diameter	4.0 in radius
Innermost clear aperture	From 1.472- to 1.726-in radii
Second clear aperture	From 2.476- to 2.726-in radii
Outermost clear aperture	From 3.226- to 4.000-in radii

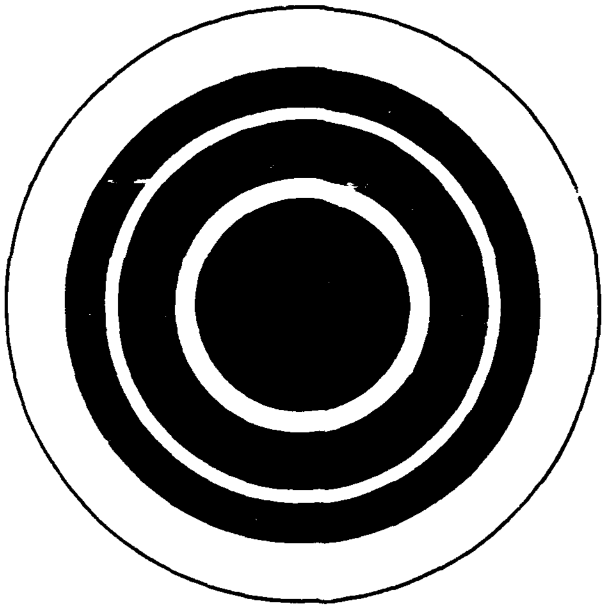

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Figure 1. Mask design

Figure 2 shows the corresponding percentage error in approximating the $z^{5/3}$ profile by adjusting $W(z)$, plotting $[W(z)/c * z^{5/3} - 1] * 100$. The value of A for this mask is 0.0156 m^2, and the value for c is 8.847×10^{-17} m^4. As seen in Figure 2, the approximation error is quite small. At zenith angles less than 60°, and under all but the most severe atmospheric conditions, contributions to Equation (2) are insignificant outside 0.5 to 40 km. Errors are less than +3 percent over the most crucial 0.5- to 20-km range, where the C_n^2 profile is most significant under "good" atmospheric conditions.

Plugging in constants, for this mask the relation between isoplanatic angle and starlight intensity variance is

$$\theta_0(\phi_z, \lambda) = 0.443146 \sec^{-8/5}(\phi_z)\left[\sigma_S^2(0)\right]^{-3/5} \mu\text{radians} \tag{4}$$

Note that the zenith-angle dependence of the isoplanatic angle here assumes that the C_n^2 profile of the atmosphere is only a function of height, or that conditions are locally constant. For poor atmospheric sites (such as Lexington), this assumption can be invalid.

Walters has developed a technique for verifying proper isoplanometer operation.[9] Data are collected by rapidly (every few minutes) changing between stars with different zenith angles. Equation (1) indicates that a log-log plot of normalized variance vs zenith angle, as shown by Walters, should be linear with a slope of 8/3. The degree to which the measured data points fit this linear plot serves as a test of proper isoplanometer operation. This is valid, however, only if (1) the normalized variance is not saturated, and (2) when C_n^2 is only a function of height. If the atmospheric conditions are constant over long periods, an equivalent method is to track the same star as zenith angles change; however, "constant" atmosphere is rarely the case, even for good astronomical sites.

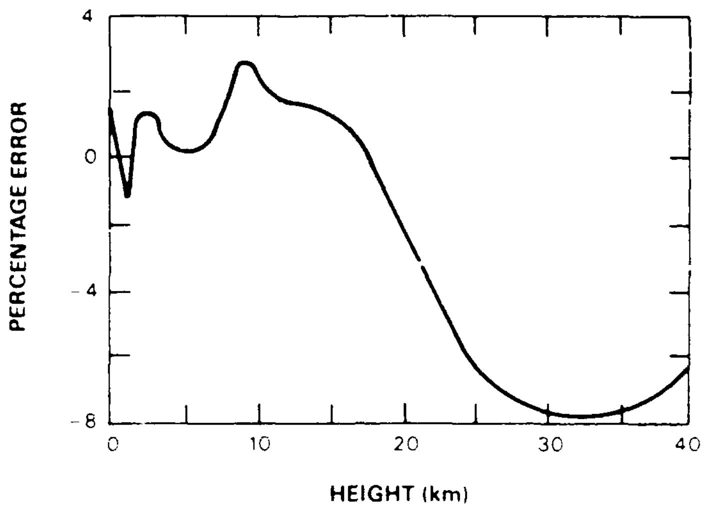

Figure 2. Percentage error for three annuli design.

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III. THE INSTRUMENT

The experimental setup is shown in Figure 3. The primary components consist of a Celestron 8-in F/17 Schmidt-Cassegrainian telescope, an apodizing mask, an optical detector assembly, a high-voltage power supply, processing electronics, an oscilloscope, and a computer controller. The optical detector assembly consists of a black anodized aluminum tube which contains a beamsplitter, a 25-mm reticled eyepiece, a narrowband filter, and a photomultiplier tube, as shown in Figure 4. Starlight passes through the mask, through the telescope, and hits the beamsplitter. A portion of the light is split off to the eyepiece, which is used for alignment and tracking purposes. The exact amount of light split off is not important, since the isoplanatic angle calculation is independent of the absolute signal level. The remaining light passes through a 100-Å-wide optical filter centered at 5000 Å. The resulting light is placed on a photomultiplier tube (PMT). In order to increase the image size on the tube, the PMT is placed nominally at 1 in behind the back focal plane of the telescope. Using a larger than diffraction-limited spot reduces the effects of PMT nonuniformities. The PMT (an Oriel 77340) is powered by an Oriel model 7070 high-voltage power supply and current monitor.

The electronics unit was designed by E. Coragiuri to compute certain statistics of the output current signal from the PMT. It consists of a transimpedance amplifier, followed by a voltage amplifier, variable-bandwidth 5-pole low-pass filter, 12-bit A/D converter, and interface logic. The A/D samples the resulting signal at a 1-kHz rate, and digital logic computes the sum of the samples and the sum of the square of the samples. The bandwidth of the scintillations rolled off below 300 Hz, therefore no aliasing should have occurred. These scaled versions of the first and second moments of the received optical power S are transmitted across an IEEE-488 bus to the IBM-AT computer controller. A Hitachi 6301 microprocessor controls the interface and the triggering of requests from the controller. The digital processing could have been done by the IBM-AT alone; however, the AT was intended to control another device simultaneously, and it was therefore determined to offload the easy, but software time-consuming task to a dedicated board. The input to the

A/D (the low-pass filtered, scaled version of the PMT output) was also sent to an oscilloscope, which provided a useful diagnostic aid. By triggering the electronics unit, the AT returned the sum of the samples (denoted Σx_i) and the sum squared of the samples (denoted Σx_i^2).

Based on N = 1000 samples, the AT first calculates the normalized variance defined as

$$\sigma_\chi^2(\phi_z) = \frac{\text{variance}}{\text{mean}^2} = \frac{\frac{1}{N}\sum_{i=1}^{N}[\alpha X_i]^2 - \left[\frac{1}{N}\sum_{i=1}^{N}\alpha X_i\right]^2}{\left[\frac{1}{N}\sum_{i=1}^{N}\alpha X_i - b\right]^2} \tag{5}$$

In this equation, α is the A/D scaling constant, and b is the sky background level which must be subtracted from the mean since it is unrelated to the starlight, and otherwise would decrease the variance. The value of b is computed as the arithmetic mean of five samples of the background level taken just out of the field-of-view of the star to be tracked. Next, the raw isoplanatic angle $\theta_0(\phi_z,\lambda)$ is computed by scaling the normalized

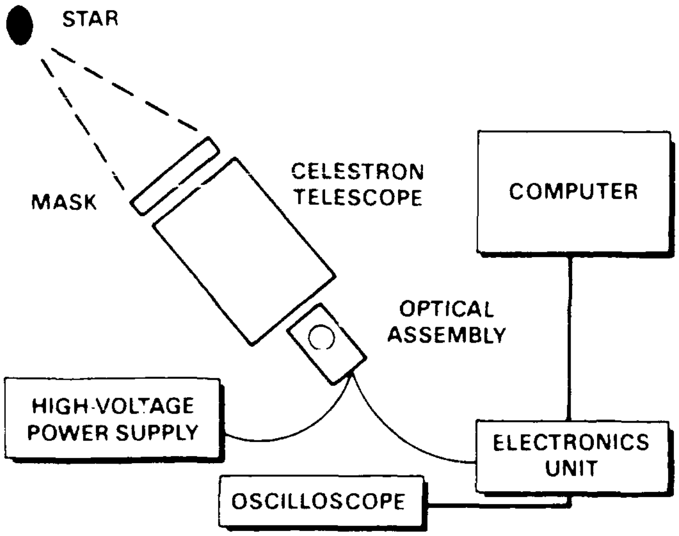


Figure 3. Experimental setup

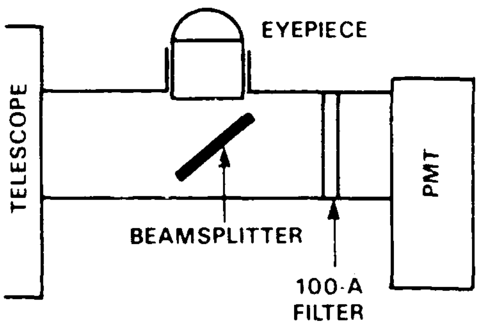
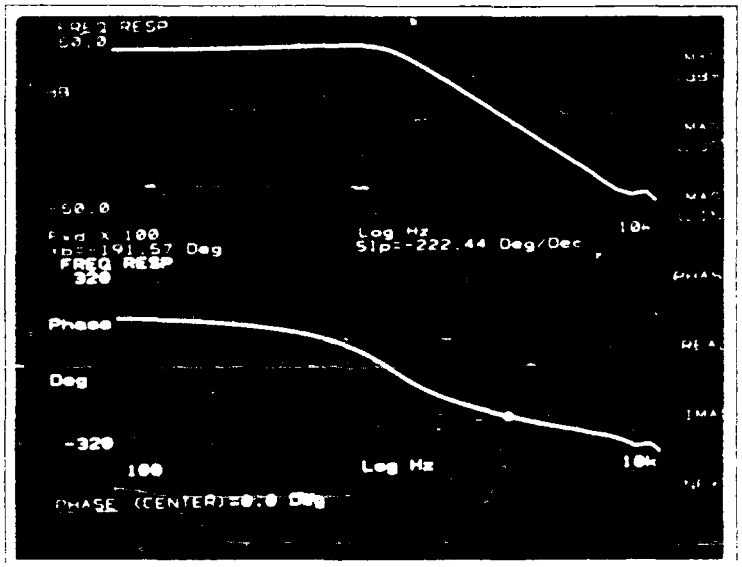


Figure 4. Optical detector assembly



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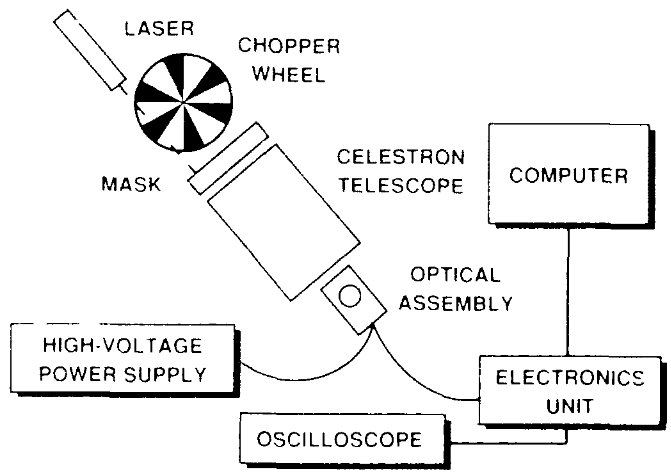

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variance. Finally, the raw isoplanatic angle is converted to a zenith-corrected isoplanatic angle $\theta_0(0,\lambda)$ by dividing the raw isoplanatic angle by $\sec^{-8/5}(\phi_z)$.

IV. VERIFICATION

The isoplanometer was calibrated in two stages — first electrically and then optically. First, an HP3562A dynamic signal analyzer was used to electrically verify the transimpedance amplifier/voltage amplifier/filter combination in the electronics unit. In order to emulate the PMT output, a 1-MΩ series resistor was used to convert the signal generator voltage source to a current source. Gains and offsets were trimmed as appropriate. The current-to-voltage transfer function of the electronics unit is shown in Figure 5. The 3-dB point is sufficiently high to pass nearly all stellar intensity fluctuations. This low-pass filter limited PMT noise, and reduced sample aliasing. Noise measurements verify that PMT shot noise is well below sampling resolution.

Next, a function generator was connected to the electronics unit, and a square wave of known amplitude, frequency, and DC offset was input. It was verified that the isoplanometer system properly computed the mean, variance, and normalized variance statistics of this waveform.

Finally, the setup shown in Figure 6 was used to perform an equivalent optical calibration. A HeNe laser was sent through a 50/50 chopper wheel, and the chopped beam was directed through the telescope and on to the PMT. The A/D input signal from the electronics unit was observed on the oscilloscope, and it was verified that the correct statistics were computed.

V. THE EXPERIMENT

Unfortunately, the instrument tests originally planned for Mt. Wilson were canceled due to the LITE program funding cuts. A comparison run of our instrument with Professor Don Walters' isoplanometer was similarly canceled.[9] Uncooperative weather conditions in Lexington, Massachusetts during the month of July permitted only three evenings of measurements, two of which were required to debug the setup. Data collected on the remaining evening of 25 July 1988 are reported and analyzed in Section VI.

The experimental procedure was as follows. First, the telescope was set up on the A-building roof at Lincoln Laboratory, leveled, and polar aligned. Polar alignment was close enough so that the Celestron right-ascension tracking drive maintained track over the duration of each measurement. Starting with a bright star (usually Arcturus or Vega), the PMT bias voltage was set at approximately 700 V. For each star measured, the actual voltage was adjusted so that the input to the A/D averaged about 4 V, as observed on the oscilloscope. The oscilloscope also verified that the peak intensity fluctuations did not exceed the saturation voltage of the A/D (10 V). The IBM-AT software was started, and the relevant parameters were input manually. The program then requested that the telescope field-of-view be set to the background, where five background samples were taken, averaged, and stored. The telescope was repositioned on the star, and the measurement process began. The IBM-AT recorded local time, background level, mean and variance from the electronics unit, raw and corrected isoplanatic angles, and the zenith angle.

Nominally, 5 min of continuous data were taken per star measurement. Each trial consisted of $N = 1000$ samples taken at a 1-kHz rate, for a total of 1 s of data. The system could manage approximately 50 trials per minute. A subtle problem in the electronics unit prevented continuous measurement. Once a set of trials (usually 200 or 250) was completed, another star was chosen and the process was repeated. We switched between a single pair of stars, having different zenith angles, approximately once every 10 min. Our goal was to verify the zenith-angle dependency described in Section II [Equation (4)]. On the evening of 25 July 1988, it was possible to complete approximately 50 runs between 9:30 p.m. and midnight.

VI. RESULTS

The data taken on the evening of 25 July 1988 are given in Figures 7 through 11. Measurements were alternated between the stars Arcturus and Vega, switching approximately every 10 min. From 9:30 p.m. to 12:00 p.m. local time, the zenith angle for Vega went from 24° to 11°, with a minimum of 0° occurring about 11:00 p.m. Arcturus went from 37° to 70° during the same period.

Figure 7 shows the average zenith-corrected isoplanatic angle for each 10-min measurement session. If local atmospheric conditions are constant, then the average values on consecutive measurements should be identical for the two stars. However, this is not the case in Figure 7, except early in the evening when both stars have small zenith angles (less than 30°). There are two possible explanations for this discrepancy. One is that the turbulence on that evening might not have been direction independent (i.e., C_n^2 was a function of location and height, rather than just location).

A more plausible explanation is that the turbulence was strong and, consequently, the normalized variance was saturated. In this situation, the isoplanometer theory presented in Section II is no longer valid, and Equation (4) cannot be used. Note that, for large zenith angles in strong turbulence, the normalized variance will saturate and, thus, the isoplanatic angle will be overestimated (as in Figure 7). Previous

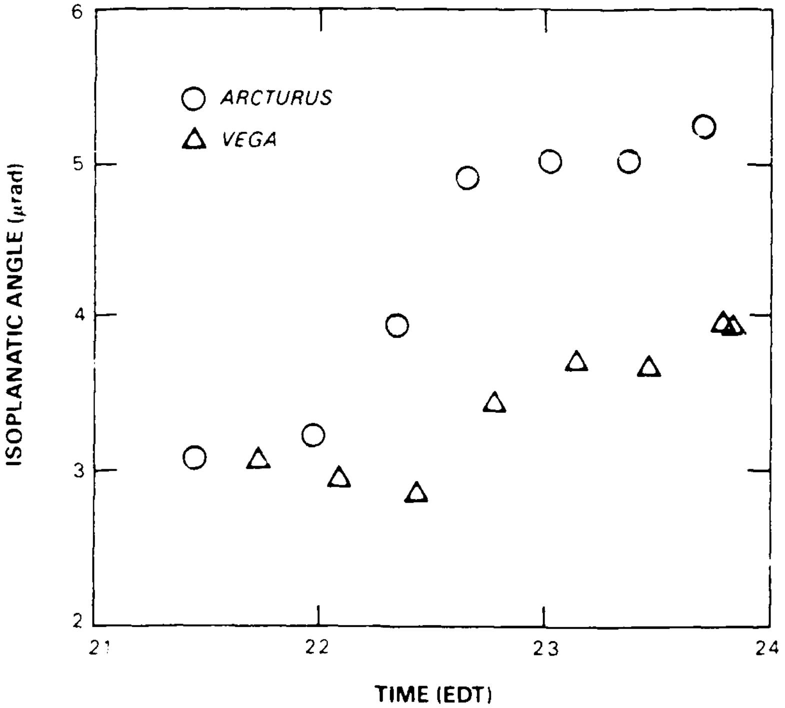

Figure 7. Average isoplanatic angle vs time.

isoplanometers built by Walters begin to saturate at normalized variances of about 0.05 (see p. 86 in Reference 3). While tracking the star Vega normalized variances were about 0.02 to 0.03. However, while tracking Arcturus, normalized variances were 0.06 or above after the initial data set. Note that the isoplanatic values for Arcturus are higher than those for Vega; under saturated variance conditions, the isoplanatic angle will be overestimated. It is plausible that the instrument was correctly calculating isoplanatic angle early in the evening, and later for Vega only. Arcturus values later in the evening were saturated, and therefore incorrect. However, this cannot be stated as a certainty.

Figures 8 and 9 show the complete isoplanatic angle data collected for Vega on the evening of 25 July 1988. Figures 10 and 11 show similar plots for Arcturus on the same night. Note that, on these plots, "dropouts" are apparent. These represent tracking errors (telescope not staying aligned on the star) or, in some cases, clouds interfering with the measurement. Such effects were taken out by post-processing, and are not reflected in the analysis here.

Figures 12 and 13 plot the normalized variances vs the secant of the zenith angle on a log-log scale, as suggested by Walters,[10] for both data sets, and for Arcturus only. The slope of the linear fit is below the predicted 8/3 value, a result consistent with a saturated normalized variance.

Finally, Figure 14 shows the saturation isoplanatic angle as a function of zenith angle. Data points above or to the left of the saturation line are considered valid; those below or to the right of the line are considered not valid. Note that all data for Arcturus are within the invalid region, while data for Vega are either unsaturated or marginal. Therefore, comparing estimates of isoplanatic angle made with Vega with those made from Arcturus is invalid. Also note that if a fully operational instrument existed, this technique could be used to predict poor atmospheric conditions (i.e., as low as 4-μrad angle at 0.5 μm), as long as a reasonably bright star existed at zenith angle less than 38°.

VII. CONCLUSIONS

Group 67 has designed and built an isoplanometer. The theory of this device is based on the well-known scintillation averaging approach. The device was operated in Lexington, Massachusetts for verification purposes. Lexington is a poor astronomical site, and often exhibits a high level of turbulence. Consequently, isoplanatic angles can be very low and the normalized variance may saturate under almost all conditions in Lexington. The instrument was designed to accurately measure isoplanatic angle when the angle is above approximately 5 to 6 μrad at 5000 Å, the approximate requirement for the LITE experiment. Initial plans for device verification included co-location with another isoplanometer at a high-quality astronomical site, where isoplanatic angle levels would reach 7 to 10 μrad at 5000 Å. The wavelength scaling to 0.86 μm (the LITE operating wavelength) would be a factor of 1.919, giving isoplanatic angles above 14 μrad at this wavelength at a good site. Unfortunately, this extensive verification was not possible and, therefore, verification of device operation was not completed. However, results indicate expected operation under the given conditions in Lexington. Verification testing of this instrument would therefore require that it be placed at a "good" astronomical site, such as the Mount Wilson Observatory.

It should be noted that Rein Teoste and Jim Daley of Lincoln Laboratory's Division 5 have performed isoplanatic angle measurements at Firepond using an instrument built by Don Walters. They reported[11] isoplanatic angles on the order of 5 μrad.

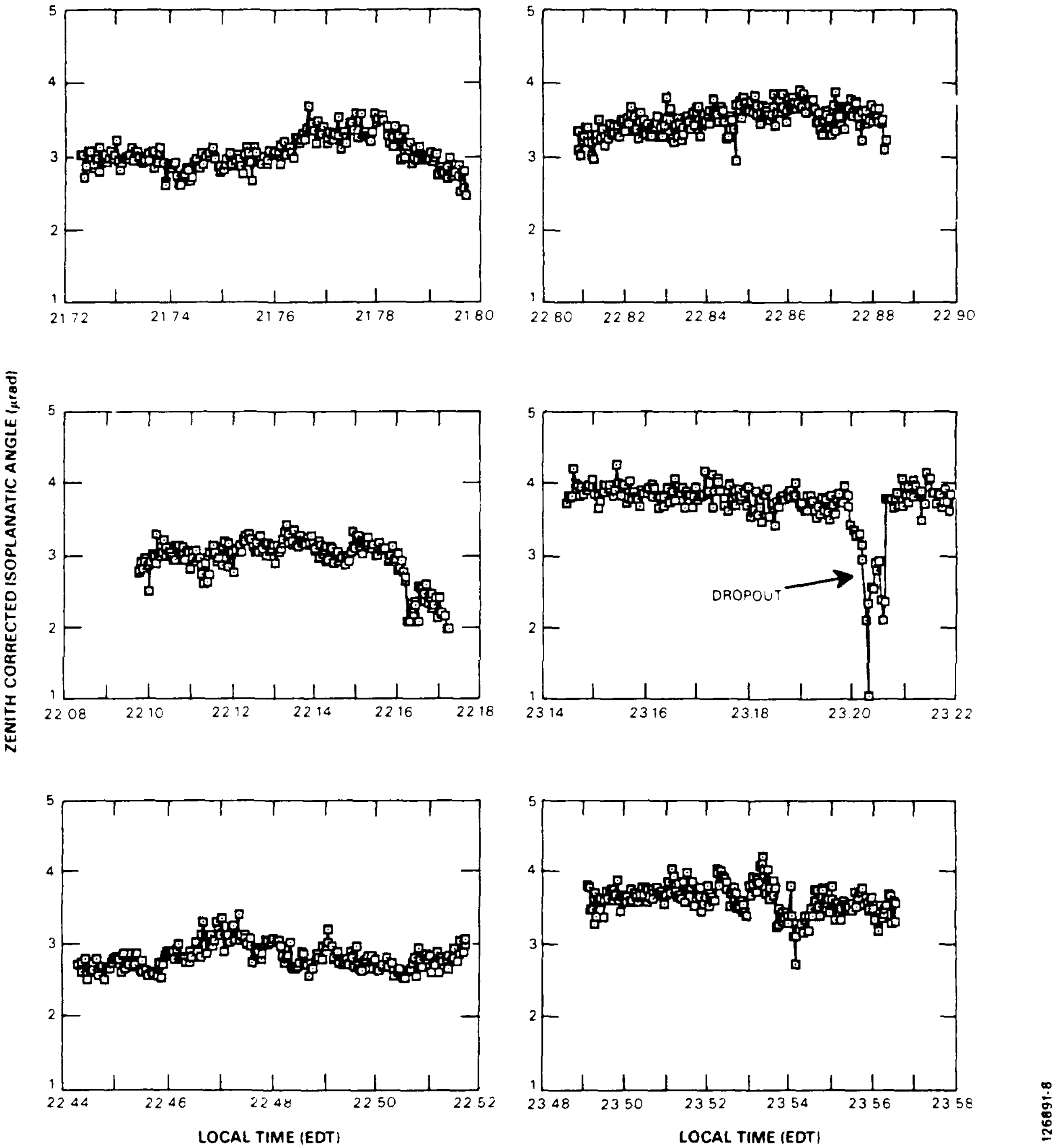

Figure 8. Isoplanatic angle estimated from Vega

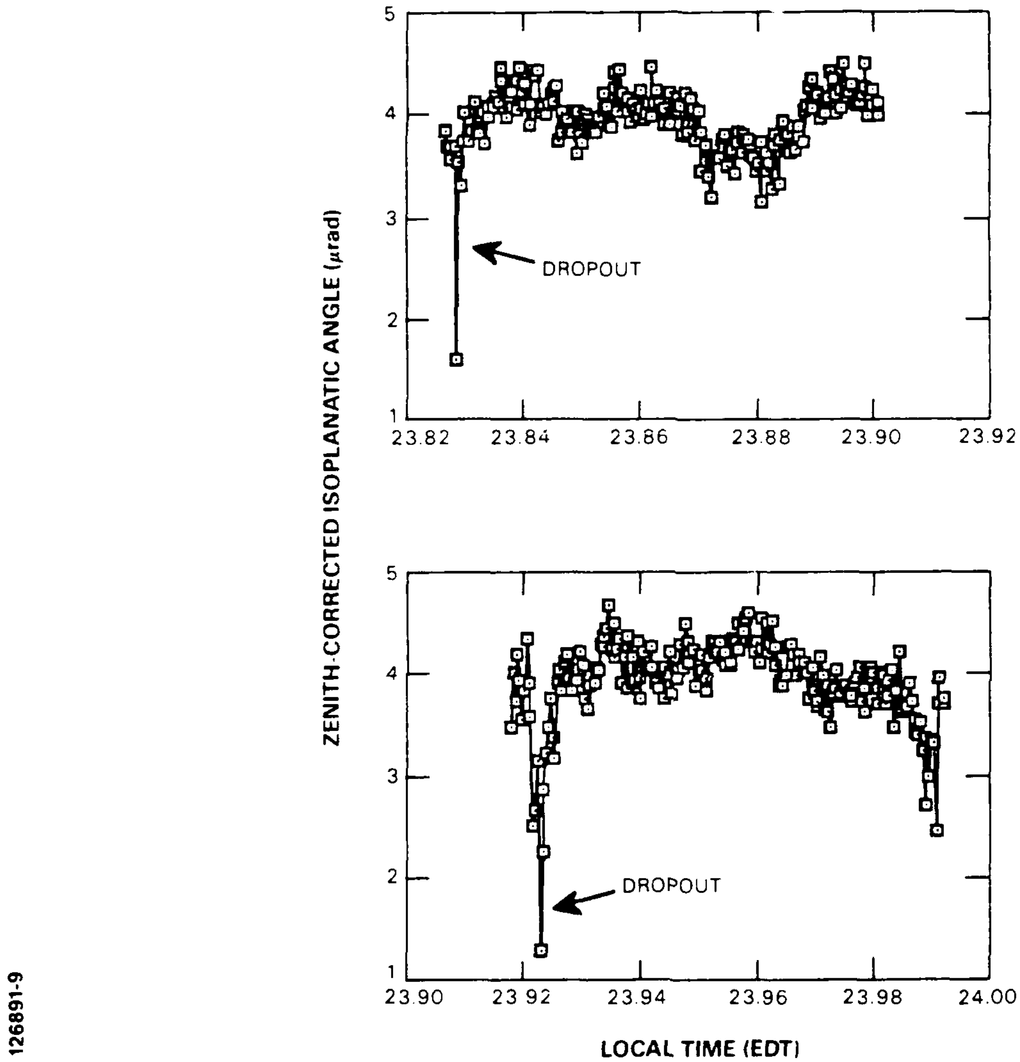

Figure 9. Isoplanatic angle estimated from Vega

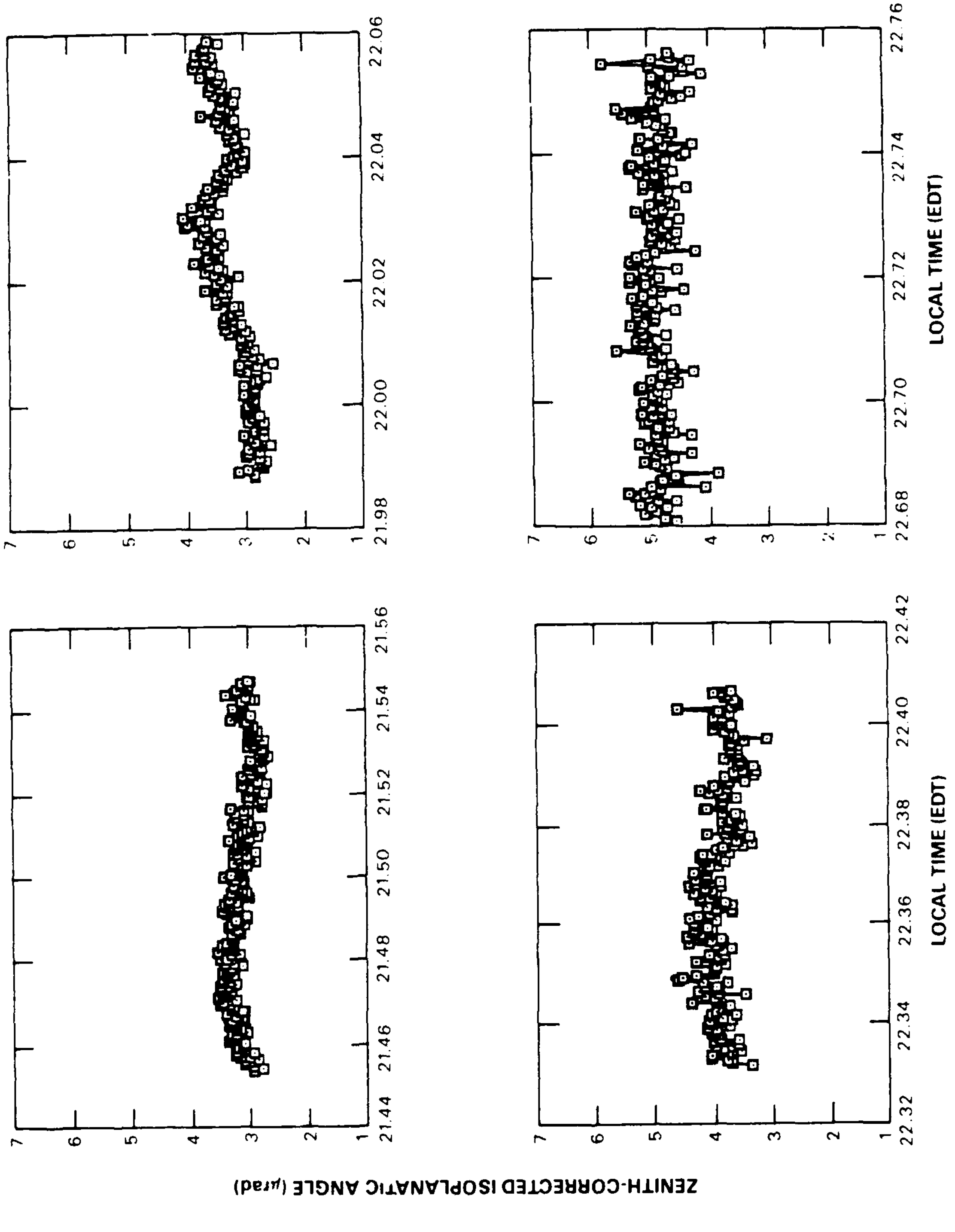

Figure 10. Isoplanatic angle estimated from Arcturus.

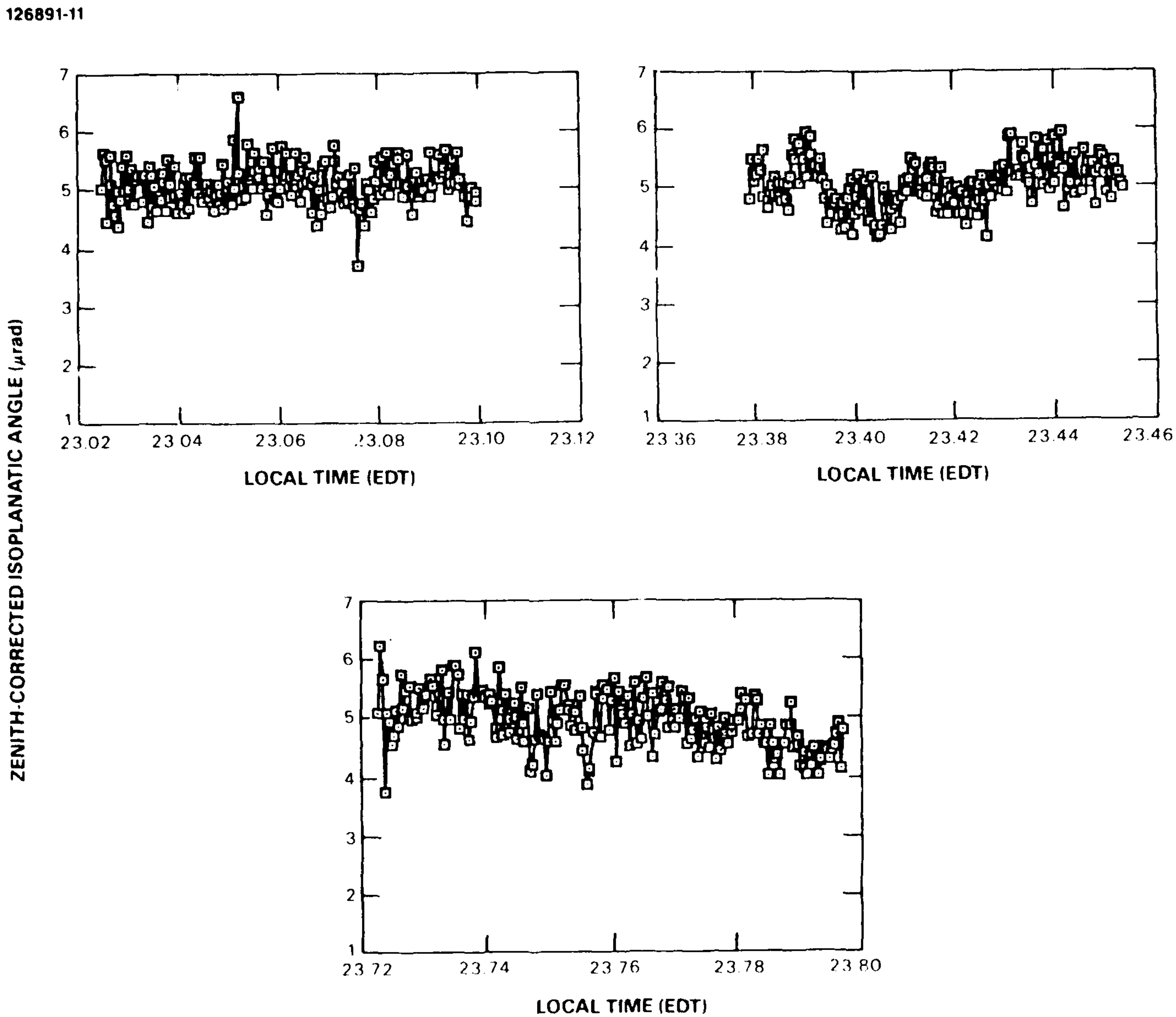

Figure 11 Isoplanatic angle estimated from Arcturus

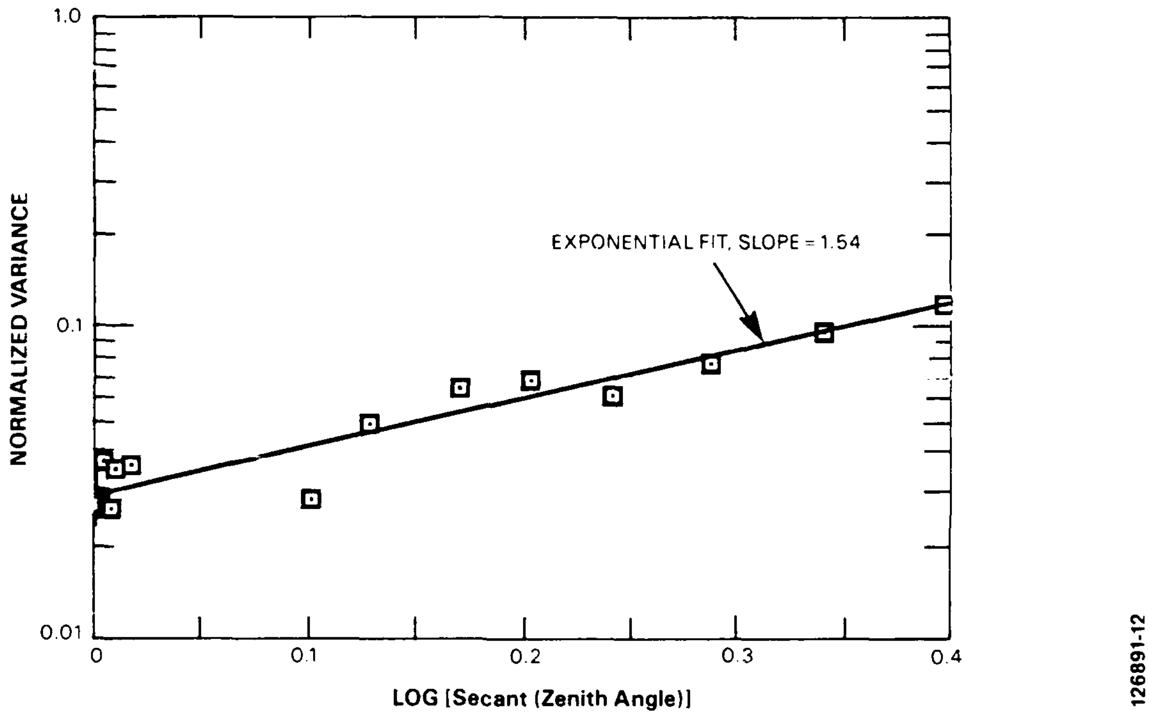

Figure 12. Normalized variance vs secant (zenith angle).

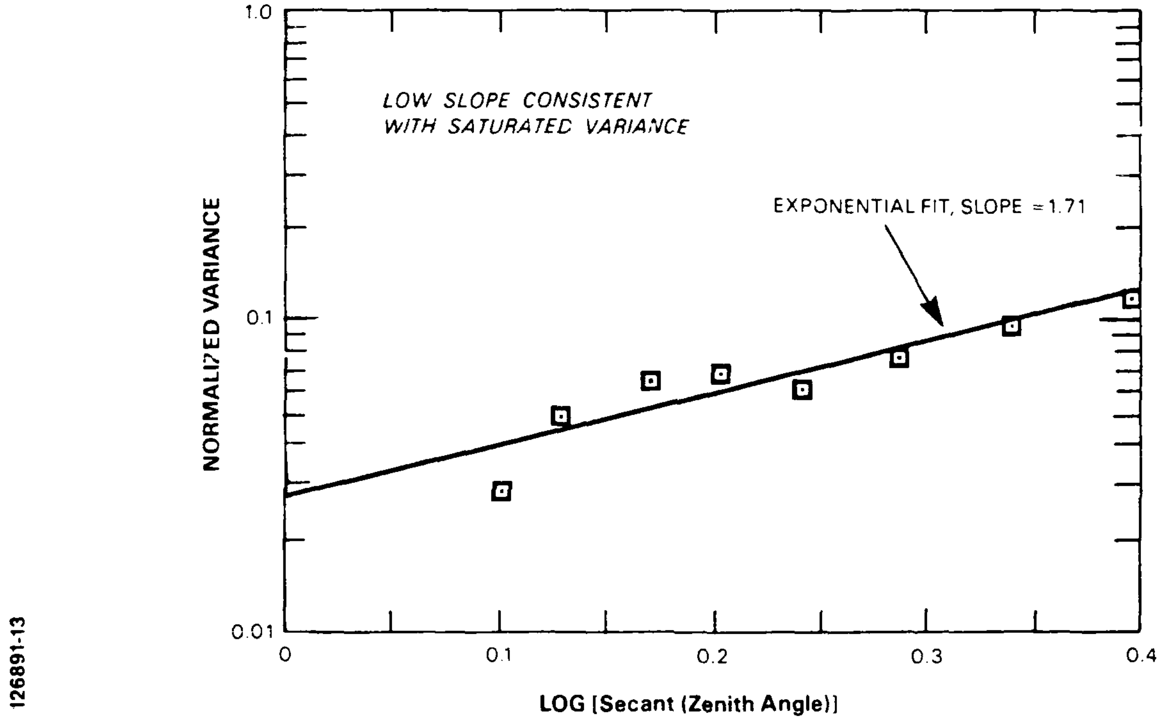

Figure 13. Normalized variance vs secant (zenith angle), Arcturus only.

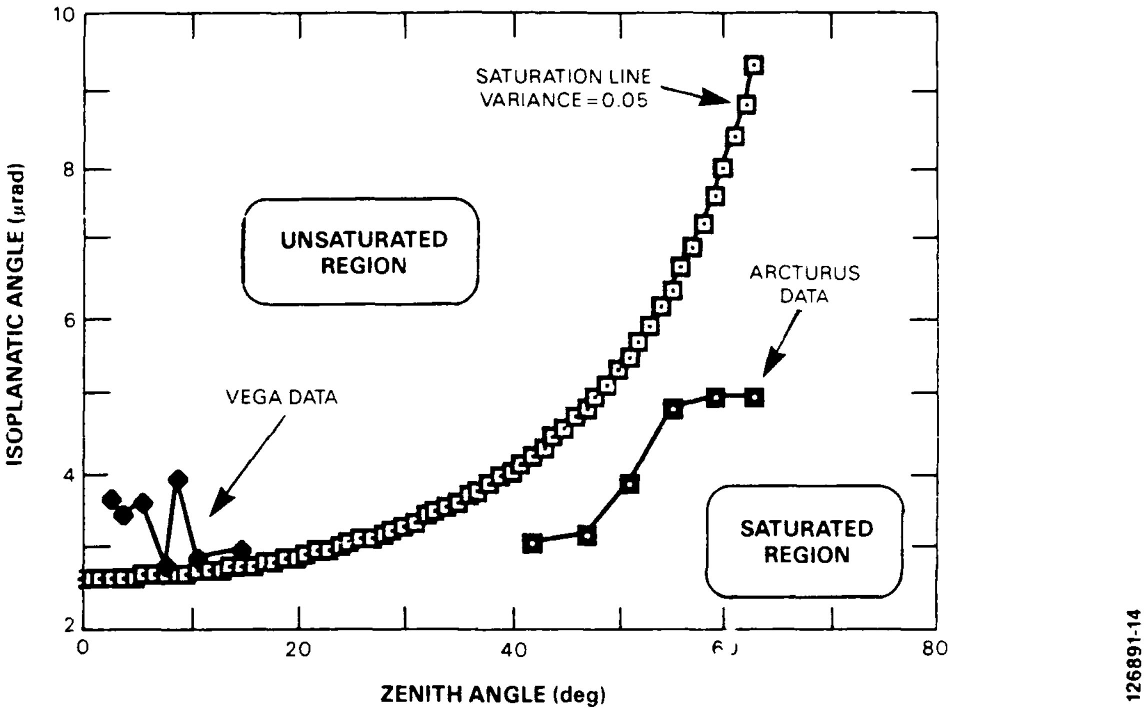

Figure 14. Scintillometer saturation curve and data for 26 July 1988.

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